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SEDIMENTOLOGY OF GAS-BEARING DEVONIAN SHALES OF THE APPALACHIAN BASIN

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ABSTRACT

The gas-bearing shales of the Appalachian Basin are chiefly of Middle and Late Devonian age with minor contributions from shales of Early Mississippian age. Most of the gas production comes from the west-central and western parts of the Appalachian Basin (Figure 1) where these shales extend from the outcrop to depths of as much as 8,000 feet. Here an estimated 2.7 trillion cubic feet have been produced and today there are about 9,600 producing wells (U.S. Department of Energy, 1980, p. III-6). About 8,000 of these wells are located in eastern Kentucky, western West Virginia, and south-eastern Ohio. Conservative estimates of gas that can be recovered from Devonian shale vary between 1.7 to 25 Tcf, although an upper boundary of as high as 903 Tcf has been reported (U.S. Department of Energy, 1980, Chapter 3, Table 301). The first well drilled specifically for natural gas in the United States was located in the Appalachian Basin in Fredonia, Chautauqua County, New York, and obtained gas production from the Devonian shale sequence in 1821 over 38 years before the Drake well produced oil in Pennsylvania (Piotrowski and Harper, 1979, p. 1).

The Eastern Gas Shales Project (1976-1981) of the U.S. Department of Energy has generated a large amount of information on Devonian shale, especially in the western and central parts of the Appalachian Basin (Morgantown Energy Technology Center, 1980). Below we summarize much of this, emphasizing the sedimentology of the shales and how it is related to gas, oil, and uranium.

We report this information in a series of statements each followed by a brief summary of supporting evidence or discussion and, where interpretations differ from our own, we include them. We believe this format is the most efficient way to learn about the gas-bearing Devonian shales of the Appalachian Basin and have organized our statements as follows: paleogeography and basin analysis; lithology and internal stratigraphy; paleontology; mineralogy, petrology, and chemistry; and gas, oil, and uranium.

PALEOGEOGRAPHY AND BASIN ANALYSIS

In the Middle and Upper Devonian, the Appalachian Basin was located along the margin of the "Old Red Sandstone Continent."

The "Old Red Continent" (Figure 2) was a large land mass including much of the present Canadian Shield, Greenland, Scandinavia, and British Isles (House, 1968; Friend, 1969; Greiner, 1978). The gas-bearing shales of what is now the Appalachian Basin accumulated around its margins near the equator (Ettensohn and Barron, 1980, figure 4) and were derived from the ancestral Acadian Mountains to the east.

The gas-bearing shales of the Appalachian Basin are part of a large delta complex that is unusual in that it prograded cratonward into a euxinic basin with very widespread black shales.

Rich (1951, figure 1) early emphasized the relationship of the black shales to the Devonian delta and thought they had a relatively deep water origin. It was Barrell (1913 and 1914), however, who more than 50 years ago drew major attention to this large -- greater than 280,000 km^2 -- and unusual delta in Pennsylvania and adjacent states. Since then many sedimentologists and stratigraphers have studied it, although few have attempted to see it in its entirety. Much about the shale has been published by the U.S. Geological Survey, especially by Wallace de Witt and his coworkers (see for example, de Witt et al., 1975; Oliver et al., 1971; Harris et al., 1978).

The Devonian delta complex of the Appalachian Basin had a westward flowing river and marine dispersal system.

Regional paleocurrent mapping in outcrop unequivocably demonstrates westward paleoflow (Figure 3) and studies of paleocurrent structures in oriented cores fully corroborate abundant outcrop data. Wood fragments in the shales (Figure 4) are exceptionally good indicators of paleocurrents in cores, are nearly always well oriented and easy to measure (Figure 5). Well-oriented sole marks on very thin -- only a few millimeters thick -- siltstones are also common.

The uniformity of paleocurrents is unusual for a basin of this size and is difficult to explain. One factor to consider is that the Upper Devonian delta, unlike all modern ones, prograded toward the craton.

No evidence for contour currents (currents that parallel the bathymetry of the basin) has been found.

The Upper Devonian of the Appalachian Basin forms a westward-thinning wedge within which there is a classic transition from shelf → slope → basin.

Cross sections by Willard (1939), Rich (1951), Oliver et al., (1967 and 1971), and Heckel (1973) all show this, as do later east-west cross sections based on gamma-ray stratigraphy (see Roen et al., 1980, for a compilation of the many recent cross sections of the shale sequence in the basin and Piotrowski and Krajewski, 1979, for a very detailed/network of cross sections in Pennsylvania). Figure 6 shows some of the diverse ways in which this wedge has been illustrated and Figures 7 and 8 show the results of some of the most recent thinking.

Essential environments of the basin model include an alluvial plain in far eastern Pennsylvania with a high rate of sedimentation, a coupled delta plain and shelf, a slope with turbidites, and a euxinic basin with a very slow rate of sedimentation.

The above depositional environments form, from east to west, a well-organized depositional system (Figure 9). Alluvial environments in the Catskill facies have been documented by Allen and Friend (1968), Walker (1971) and many others, the delta plain-shelf by Glaser (1974) and Sutton et al. (1970), the turbidites by McIver (1970) and Lundegard et al. (1980) and the euxinic basin by Rich (1951), Broadhead (1980), and Broadhead, et al. (1981). This system migrated westward with time as shown by the cross sections and by vertical profiles of mineralogy and geochemistry (Hohn et al., 1980).

Turbidite siltstones and sandstones form a thick lens in western Pennsylvania.

These turbidites are below the Chemung facies (Figure 8) and appear to be lithologically equivalent to the Brallier Formation in the outcrop of Pennyslvania, Maryland, and West Virginia, and equivalent to the Java and post-Java beds in New York. In Ohio these turbidites and their interbedded silty, greenish-gray shales are found in the Chagrin Shale.

Original water depth of the black shales has long been controversial, but sedimentologic evidence suggests that they were everywhere deposited below the dysaerobic-anaerobic boundary which, over most of the basin, occurred at a water depth of 100 to 200 meters.

Identification of the turbidites in the basin is central to this interpretation: the distal turbidites of the prodelta slope "finger out" down dip into black shale (Figures 7 and 9) and the Chagrin and Brallier, which were largely deposited by turbidity currents on a slope and base of slope, thin westward into black shale, but pass eastward into shallow water clastics. Supporting evidence is also provided by the geometry of the Foerstia (Protosalvinia) zone, a biostratigraphic marker defined by a marine alga, and by the study of trace fossils (see Paleontology). But see Nuhfer et al. (1979) and Schwietering (1979) for an opposing view of the depth of water in which the black shales accumulated.

In the Cumberland Saddle area of south-central Kentucky, the black shale section is greatly condensed and thin, is all of Upper Devonian and Lower Mississippian age and extends continuously between the Appalachian and Illinois Basins.

By analogy, the Cincinnati Arch, north of the Cumberland Saddle, was probably not exposed during the Upper Devonian, although part of it may have been earlier in the Devonian, as shown by the onlap of Middle Devonian units onto the Cincinnati Arch.

LITHOLOGY AND INTERNAL STRATIGRAPHY

Practical stratigraphy of the black shale sequence is based on the distribution of uranium.

Both standard subsurface gamma-ray logs and scintillometer surveys made in outcrop (Provo et al., 1978; Ettensohn et al., 1979) are basic to understanding the internal stratigraphy of the Devonian shales (Figure 10). Uranium is the most important element contributing to response of gamma-ray logs (see Geochemistry for more discussion of uranium).

Black shales in the basin have, almost without exception, sharp bases and grade, both upward and eastward, into gray and greenish-gray shales.

The sharp base (Figure 11) represents a sudden deepening of water in the basin followed by a more gradual westward progradation of delta-front sediments. Eastward, carbon content and radioactivity decrease in black shale tongues. This variation makes it necessary to choose carefully radioactivity cutoffs on gamma-ray logs when defining the different types of shale within the basin.

The Devonian rocks of the Appalachian Basin had several depositional centers along their eastern margin which broadly controlled facies distribution within the basin.

Examples of these are the Wyoming, Snyder, Fulton, and Augusta Lobes (Dennison and Head, 1975, Figure 12). Paleocurrents and total Upper Devonian isopach (Figure 3 and Oliver et al., 1971, sheet 7) provide additional evidence, and as early as 1939, Willard (Figure 71) outlined areas on the southeast side of the basin where rivers emptied into black shale deposition appears to have been greatest marginal to subsea fans related to these depositional centers. Hence, the identification and mapping of distal and medial subsea fans and their relation to the deposition of black shales deserves the attention of those exploring shaly basins for gas.

Depositional strike varies somewhat within the basin and is related to depositional centers along the eastern side of the basin which, to some degree, shifted laterally with time.

In western Pennsylvania depositional strike closely parallels present structural strike and is commonly N 30° to 40° E (Piotrowski and Harper, 1979) whereas along much of the western part of the basin it is largely north-south (Figure 3) parallel to regional isopach. In the southeastern part of the basin, depositional strike is south-southeast (Figure 3 and Oliver et al., 1971, sheet 7).

Thin units, some as thin as tens of centimeters, can be traced along depositional strike for hundreds of kilometers.

An excellent, well-documented example, which occurs in the western part of the basin is the Three Lick Bed, a thin distinctive interbedded sequence of greenish-gray and black shales (Provo, Kepferle, and Potter, 1978). Such thin, far-ranging units point to the very widespread extent of many of the sedimentary environments in the Devonian shale basin.

All Upper Devonian shale units clearly have coarser clastic equivalents eastward: greenish-gray shale → siltstone → sandstone (some of which form a red bed facies).

These coarser clastics are well documented in New York (Rickard, 1975) and Pennsylvania (Piotrowski and Harper, 1979, figure 6) where cyclic facies changes possibly can be related to tongues of black shale.

Basinal lithologies are virtually all shale.

Coarse clastics were trapped in the east by the Catskill delta plain and upper part of the delta front and most silts were trapped at the base of slope of the delta nor was there a source of clastics from the west. Primary carbonates in the Upper Devonian are very rare because water was usually too deep or too low in oxygen for carbonate-secreting organisms and because mud was very abundant.

Seven major black shale units occur in the basin.

These units include the Middle Devonian Marcellus shale and the Upper Devonian Geneseo-Burkett, Middlesex, Rhinestreet, Huron-Dunkirk, and Cleveland shales and the Lower Mississippian Sunbury shale as can be seen from comparison of sections published by Rickard (1975), Wallace et al. (1977), Schwietering (1979, pls. 1 and 2) and Broadhead (1980, figure 4).

The fundamental causes of these cycles have yet to be uniquely identified.

Ettensohn and Barron (1980, p. 67) have related them to variations of terrigenous supply, but another possibility is widespread transgressions caused by eustatic changes in sea level.

Two unconformities occur in the shales in the western part of the Appalachian Basin.

Schwietering (1979) documents these unconformities in Ohio: one at the base of the Olentangy shale (separating it from Lower and Middle Devonian limestone) and another within the Olentangy at the base of its upper part (forming the base of the Devonian).

The shale-on-shale unconformity within the Olentangy may be analogous to those that have been found in the subsurface of continental margins.

Seismic stratigraphy (Payton, 1977) and deep-sea drilling have documented unconformities in the deep ocean and its margins, where subaerial erosion seems most unlikely. Could shale-on-shale unconformities in continental basins have a comparable origin? On the other hand, a deep-water origin for an unconformity is unlikely where the underlying unit has a probable shallow water origin -- for example, the limestone underlying the unconformity at the base of the Olentangy or where locally well-sorted sandstones occur along an unconformity as at the base of the Devonian shales in southern Kentucky and Tennessee (Conant and Swanson, 1961, p. 25-28).

Shale units in the basin are distinguished by color and, hence, by carbon content.

In marine environments shales are almost always greenish-gray, gray, or black. Carbon content correlates closely with these colors (Figure 12) and, therefore, can be quickly and roughly estimated in both outcrops and cores. Carbonate content is a secondary factor and decreases darkness of shale colors.

Black, bituminous shales are laminated and lack bioturbation, whereas greenish-gray shales may be either laminated or nonlaminated and if the latter, have appreciable bioturbation.

Interrelationships among color, lamination, and bioturbation have been documented by Nuhfer and Vinopal (1978, p. 6) and by Cluff (1980). Black, bituminous shales were deposited in anaerobic bottom water, whereas greenish-gray shales have two possible origins: where bioturbated, they were formed by the basinward retreat of the dysaerobic-anaerobic boundary; where laminated or sparingly bioturbated, they may represent injection of oxygenated water by turbidity currents (Figure 13). In modern sediments turbidity currents have been inferred to introduce oxygen to the dysaerobic bottom waters of the Santa Barbara Basin (Sholkovitz and Soutar, 1975).

The Chagrin Shale, in parts of Ohio and western Pennsylvania and most of the Brallier Formation, in parts of West Virginia, Maryland, Pennsylvania, and Tennessee, both consist of a wedge of gray and greenish-gray shale, interbedded siltstones, and minor sandstone.

These units represent deposition on a submarine slope by distal turbidites derived from the east (Figures 7 and 9).

The Chagrin appears to be younger than much of the Brallier, although their lithologies are indistinguishable.

The Chagrin lies to the west and is "up dip" from the Brallier (Figures 7 and 9) and demonstrates the westward migration of major facies in the basin, as was early recognized by Caster (1934).

It has proved difficult to lithologically correlate subdivisions of the black shale sequence in the Illinois Basin with those in the western part of the Appalachian Basin.

Difficulty of correlation betwen the two basins may be related to different circulation patterns or to different positions of the bottom, anaerobic layer, which controls the distribution of shale color.

PALEONTOLOGY

The fossils of the black shale form a restricted group: invertebrates consist mostly of Lingula, conodonts and Styliolina; fish bones are present; and plants consist of coalified logs (Callixylon) Tasmanites, and Foerstia.

Barron and Ettensohn (1980b, p. ii and iii) reviewed all the palenotological literature of the Devonian shale sequence in the basin from which they obtained the above conclusion. They also observed that fossil diversity in the black shale facies of the central and western parts of the basin is low but becomes greater eastward where aerobic environments prevailed on a shallow, muddy, marine shelf that contains fossil assemblages more typical of open marine conditions.

Marine fossils in the greenish-gray shale include a number of benthic forms.

Lingula and some pelecypods, orthocone cephalopods, gastropods, ostracods, and foraminifera are found in additon to most of the same forms that lived in the upper and middle parts of the water column when the bottom was anaerobic (Barron and Ettensohn, 1980a, p. 54-56).

Marine fossils in the black shales are all from the upper, aerobic, and middle dysaerobic parts of the water column.

Marine fossils of the black shale include fish, conodonts, algae, and other phytoplankton, Styliolina, some brachiopods (especially Lingula), rare crinoids, and some molluscs (Barron and Ettensohn, 1980a, p. 53-66). Fossils such as Lingula, crinoids, and rare molluscs appear to have been transported from their original habitat, possibly by weak turbidity currents. Careful and systematic correlation of lithology and fossil occurrence in cores would go far to clarify the paleoecologic setting of each lithology, which might vary somewhat in a basin as large as this one.

Nonmarine microfossils are also abundant in the shale, but all were transported and were not indigenous to the black shale sea.

Microfossils such as plant spores or woody fragements, which are abundant in the shale sequence (Martin and Zielinski, 1978), can be tranported by turbulent suspension much as fine silt and clays are transported seaward by turbulent suspension because of their small size.

The Foerstia zone, a zone defined by a fossil alga, appears to be a very useful basinwide time marker, one that is identifiable in both outcrop and core, and possibly even in cuttings.

Reference papers to Foerstia (Protosalvinia) include those by Schopf and Schwietering (1970), Schwietering (1978), and Gray and Boucot (1979). In the Appalachian Basin the Foerstia zone extends from Lake Erie, Pennsylvania and New York, on the north side of the basin, southward into Tennessee. Its greater thickness to the east reflects a higher rate of sedimentation.

Conodonts are useful for high resolution biostratigraphic correlation of the Upper Devonian shale sequence in the Appalachian Basin.

Early studies of conodonts in the Devonian shales of the Appalachian Basin were made by Hass (1956) and Huddle (1963). New extraction methods of conodonts from black shales (Duffield and Warshauer, 1979) enhance the utility of conodonts as biostratigraphic keys. Conodont color also has some utility for estimating thermal maturation of the shale (Epstein et al., 1977, Harris, 1977).

Burrowed zones can be very thin and widespread.

Such zones reflect at least two possible origins: basinward retreat of anaerobic bottom water and its complete disappearance for brief intervals due to some major change in the circulation pattern or may result from deposition by turbidity currents which introduced well-oxygenated water (Figure 13).

In single beds of greenish-gray shale interbedded with black, bituminous shale, burrows filled with greenish-gray shale extend down into black, bituminous shale.

Bottom dwellers survived in the greenish-gray shale, because it was well oxygenated and burrowed into the organic-rich black mud for nutrients (Figure 14).

MINERALOGY, PETROLOGY, AND CHEMISTRY

The shale in the western part of the basin is relatively homogeneous in mineralogy and chemistry except for a few elements that correlate with carbon.

The dominant minerals are fine quartz and illite followed by chlorite, expandable clays and minor kaolinite plus some authigenic phases such as pyrite. Although the ratio of clay to quartz varies on a small scale, there are no major changes in the kinds of clays. Calcite and dolomite are common, but their distribution is irregular. The major element chemistry is correspondingly uniform, but some minor elements, particularly uranium, correlate well with stratigraphy. In the eastern part of the basin, closer to the source and where the shale is more deeply buried, greater composition variability related to grain size and to diagenesis can be anticipated.

Organic carbon is by far the most important compositional variable.

Organic carbon governs the essential chemical and physical properties of the shale, for example, color, density, resistance to weathering, radioactivity, sulfur content, and to a degree elasticity and fracture density. Of the above, radioactivity and density have a good response on wire-line logs and, therefore, are widely used to define the internal stratigraphy of the sequence. See Schmoker (1979) for the correlaton between organic matter and log response.

Carbon isotopes of organic matter become lighter westward, parallel to paleocurrents.

Parallelism of isotopic variation (Figure 15) to paleocurrents (Figure 3) suggests two sources of carbon -- terrestial carbon, derived from the east and a lighter marine carbon that became predominant in the distal, western part of the basin.

Relative sedimentation rates within the shale are reflected in the sulfur isotopes of pyrite nodules.

At slow rates of sedimentation, sulfate-reducing bacteria act more slowly and produce a larger isotopic fractionation, which is preserved in the pyrite sulfur (Maynard, 1980). This measurement shows that greenish-gray shales were generally deposited more rapidly than black shales and that sedimentation rates over the Cincinnati Arch were much slower than to the east.

Phosphate nodules appear at the top of the section toward the southwest in Kentucky and Tennessee.

This area was one of extremely slow sedimentation, judging by both values of sulfur isotopes and the very thin condensed section. Phosphate deposition is generally considered to show slow sedimentation far distant from clastic sources (Heckel, 1977).

Illite crystallinity in the shale reflects provenance rather than diagenesis.

Vitrinite reflectance increases steadily eastward with increasing burial depth, but illite crystallinity is very uniform except in the deepest parts of the Appalachian Basin. Apparently, the basin was being supplied with well-crystallized illite from a low-grade metamorphic terrain, and this illite was, therefore, insensitive to diagenetic temperatures.

The best way to study shales petrographically is by radiography and thin sections.

Radiography (Figure 16) is quick and shows most of the essential structure and some mineralogy of the shale at hand specimen scale (Nuhfer *et al.*, 1979; Cluff, 1980) and thin sections provide surprisingly detailed information about mineralogy and texture (Lundegard *et al.*, 1980; Broadhead and Potter, 1981). Although it has not proved useful for routine studies, the SEM can be valuable for investigations of porosity, microfractures, and gas production (Nuhfer and Vinopal, 1978, p. 49; Vinopal, Nuhfer, and Klanderman, 1979).

Physical properties of Devonian shales are closely related to lithology and with practice possibly some can even be roughly estimated by visual inspection of cores.

A good example of the interdependence of lithology and physical properties is provided by data from the Illinois Basin where tensile strength, acoustic velocity, and hardness all increase with increasing perfection of lamination (Miller *et al.*, 1980, p. 88-89). Because lithofacies are much the same, their result should also apply to the Devonian shales of the Appalachian Basin.

GAS, OIL, AND URANIUM

Organic geochemistry is more useful than either inorganic geochemistry or clay mineralogy for understanding and developing the gas, oil, and uranium resources of the Devonian shales of the Appalachian Basin.

Organic carbon content directly controls gas and oil potential (Figure 17) and has also been found to be closely correlated with uranium content; on the other hand, mineralogy and inorganic chemistry are chiefly linked to grain size, which has little influence on oil and gas, except in so far as it is inversely related to carbon content.

Thermal maturity increases regionally toward the southeast from a vitrinite reflectance value of as low as 0.5 percent near the western outcrop to as high as 2 percent in western Pennsylvania.

This trend (Figure 18), which parallels changes in color of conodonts (Harris, 1977) seems to closely match increasing depth of burial, but folding and faulting may also enhance maturity. Vitrinite reflectance is one of the most widely used measures of thermal maturity of which there are over 50 (Heroux *et al.*, 1979).

Part of the gas production of the basin may depend on fracture systems or facies distribution and thickness related to the Rome Trough in eastern Kentucky and its eastern and northeastern extension into West Virginia and Pennsylvania.

Piotrowski and Harper (1979, p. 32-34) suggest some control by the northeast extension of the Rome Trough in Pennsylvania (informally called the Greene-Potter zone) as does Dillman (1980, p. 62) for the Rome Trough in eastern Kentucky.

Laminae, as well as fractures, can be conduits for natural gas.

Gas bleeding from laminated shales has been reported by Schwalb and Norris (1980, p. 8). Very thin siltstone and greenish-gray shale laminae -- both of which occur in bituminous shales -- deserve attention.

Greenish-gray shale interbedded with black, bituminous shale may be one of the best exploration targets for gas production.

Greenish-gray shale is more porous than black shale (Thomas and Frost, 1979; 1980, p. 592) and, hence, is a better reservoir whereas the black, bituminous shale is the source rock. The greater fracture density of the black shale allows gas to migrate into the greenish-gray shale, which probably acts as both a trap and seal to gas in the fracture systems of the black shale.

At least some of the gas in the shale appears to be sorbed rather than freely held in pores and fractures.

Indirect evidence for this conclusion comes from absorption-desorption studies of the shale using methane and other gases (Thomas and Frost, 1980, p. 151-159) -- black shale is less porous than greenish-gray shale but yields more gas per unit volume. Schettler et al. (1977, p. 453) and Schettler (1978, 1979) have also concluded that gas in the shale is held in three ways -- open pores, adsorbed on clays, and dissolved in organic matter. Dissolved gas in organic matter may be the most important factor in the longevity of production from gas shale wells.

Along Lake Erie greenish-gray shales and their interbedded siltstones have more gas shows than black, bituminous shales.

The above conclusion was obtained by projecting gas shows into an east-west cross section (Figure 19). More gas shows in greenish-gray shale is the converse of the usual belief that gas should be sought only in the black, bituminous shale.

Two geologic factors seem to control sites for oil from surface mining -- grade (percent carbon) and reserves per square km (thickness of the unit in question).

Unfortunately, these two factors are commonly inversely related; that is, virtually all black shale units become less carbon rich where they are thickest (Figure 20). Still largely unknown is the effect of thermal maturity on oil recovery by retorting. Ultimate recoverable reserves have been estimated by Janka and Dennison (1979, Table 5) at 414×10^9 barrels, which is twice the estimated potential of oil from coal in Ohio, Kentucky, Tennessee, and Indiana.

Most samples do not have much more uranium than 100 ppm.

Therefore, recovery of uranium from the shale will only be practical as a by-product, even though total reserves are very large.

Uranium concentrations are highest in Tennessee and Alabama, where carbon concentration is also the greatest.

Uranium content increases with increasing carbon content, but it is not known to what extent it is affected by other variables such as sedimentation rate, type of organic matter or even the presence of volcanic ash beds.

Internal surface area, a measure of matrix porosity, is controlled, in cores from the Illinois Basin, by depth of burial plus the amount of both carbonate and organic matter.

In all shales internal surface area should be a key factor for gas production. Data obtained by Thomas and Frost (1980,

p. 148-150) in the Illinois Basin show that surface area decreases steadily with depth of burial and with increasing carbonate content (Figure 21). Organic carbon also is positively correlated with internal surface area and a smaller pore size. If smaller pore size correlates with slower gas delivery, then the carbon-rich black shales may not always be the best gas exploration targets.

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TABLE 1: TRACE FOSSILS AND THEIR INTERPRETATION IN OUTCROP OF DEVONIAN SHALE ALONG EAST EAST SIDE OF CINCINNATI ARCH IN KENTUCKY.

STANDARD STRATIGRAPHIC SECTION		THIS STUDY		TRACE FOSSILS	ENVIRONMENTAL INTERPRETATION (AND ICHNOFACIES)	WATER DEPTH	REMARKS
CLEVELAND MEMBER		CLEVELAND MEMBER		NONE	LOWER SUBTIDAL ON SHELF?	WATER DEPTH INCREASES UPWARD FROM 50 TO 400 FEET	LITTLE OXYGEN
THREE LICK BED		THREE LICK BED		PLANOLITES-LIKE* CHONDRITES C&D, ZOOPHYCOS, PYRITIC BURROWS	LOWER SUBTIDAL ON SHELF (LOWER CRUSIANA TO UPPER ZOOPHYCOS)		VARIABLE OXYGENATED ZONES (0.1-1.0 m1/1 DISS. O_2) INTERMIXED WITH POORLY OXYGENATED ZONES
HURON MEMBER	UPPER PART	HURON MEMBER	UPPER PART	NONE	MIDDLE TO LOWER SUBTIDAL ON SHELF?		LITTLE OXYGEN
	MIDDLE PART			PLANOLITES*, CHONDRITES B*, RHIZOCORALLIUM, ZOOPHYCOS, AND TEICHICHNUS IN INTERBEDD. GRY AND BLK SH.	MIDDLE TO LOWER SUBTIDAL ON SHELF (MIDDLE TO LOWER CRUZIANA)		VARIABLE OXYGENATED ZONES (0.1-1.0 m1/1 DISS. O_2) INTERMIXED WITH POORLY OXYGENATED ZONES
	LOWER PART		LOWER PART	PLANOLITES*, CHONDRITES A*, ZOOPHYCOS*, LEICHICHNUS, TRICHICHNUS, CRUZIANA, PHYCODES, AND LAEVICYCLUS IN INTERBEDDED DOL AND SH.	UPPER TO MIDDLE SUBTIDAL ON PLATFORM AND SHELF (UPPER CRUZIANA)		
BOYLE DOLOMITE		BOYLE DOLOMITE		PLANOLITES*, CRUZIANA, AND RUSOPHYCUS	UPPER TO MIDDLE SUBTIDAL ON PLATFORM (UPPER CRUZIANA)		FULL MARINE WITH OXYGEN EXCEEDING 1.0 m1/1 DISS. O_2

***ABUNDANT**

PREPARED BY DOUGLAS JORDAN, BASED ON HIS MASTER'S THESIS (1979)

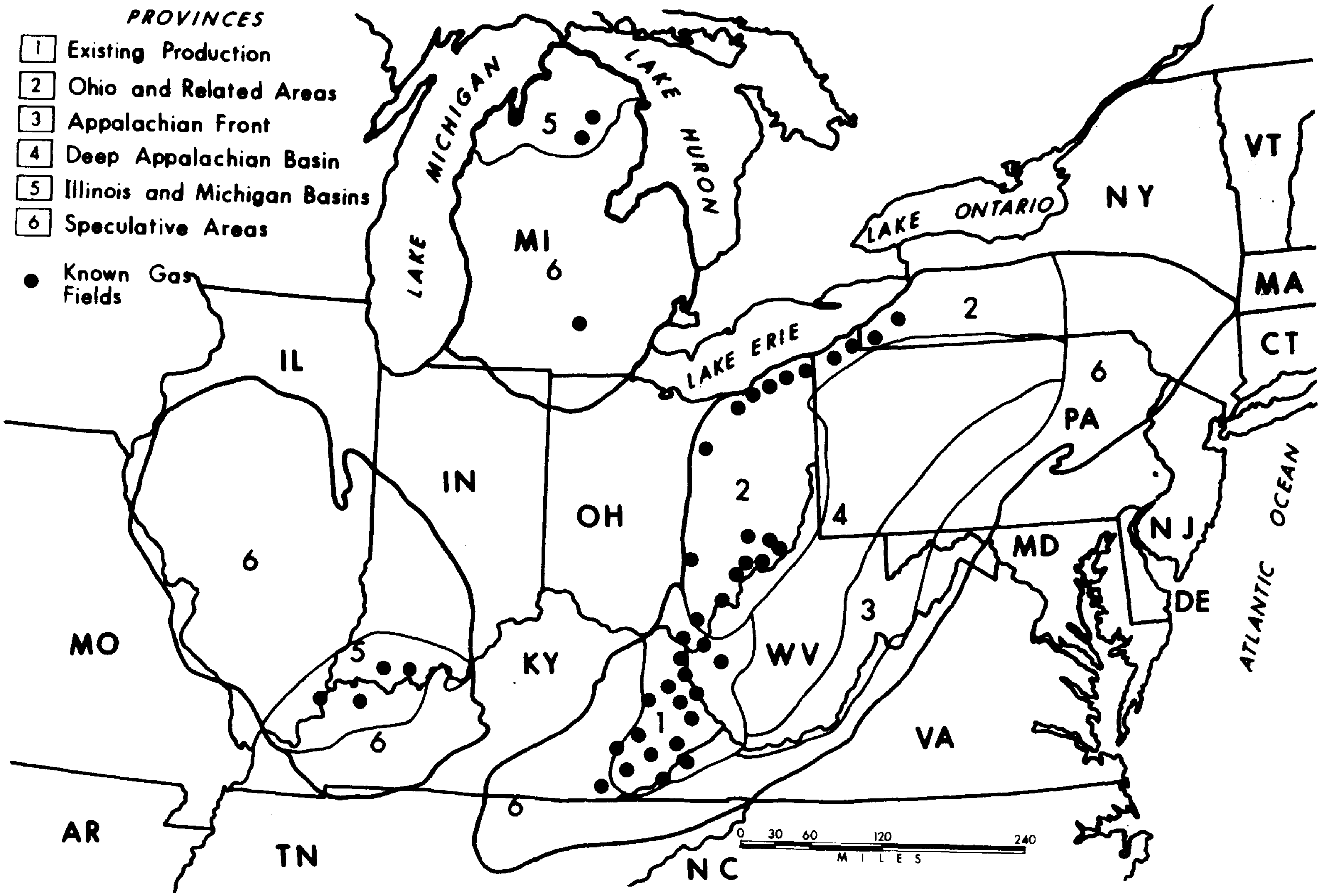


FIGURE 1: GAS PROVINCES AND PRODUCTION FROM DEVONIAN SHALES OF THE APPALACHIAN ILLINOIS AND MICHIGAN BASINS

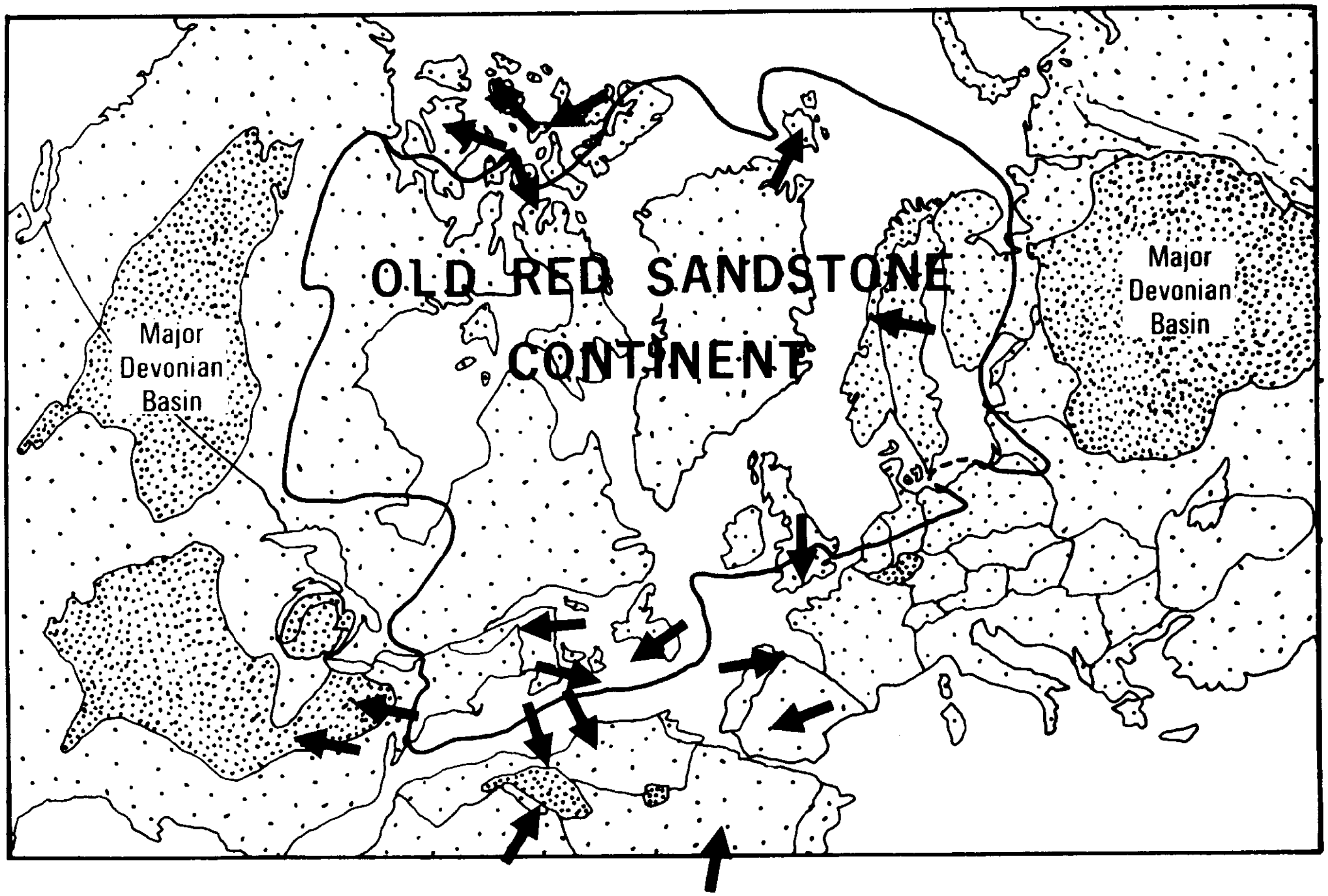


FIGURE 2: NORTH AMERICAN DEVONIAN-MISSISSIPPIAN BLACK SHALES WERE DEPOSITED MARGINAL TO AN ANCIENT LANDMASS CALLED THE OLD RED SANDSTONE CONTINENT (REDRAWN FROM HOUSE, 1968, FIG. 3). ARROWS SHOW GENERALIZED PALEOFLOW (DATA CHIEFLY FROM GRIENER, 1978, FIGS. 2 and 3).

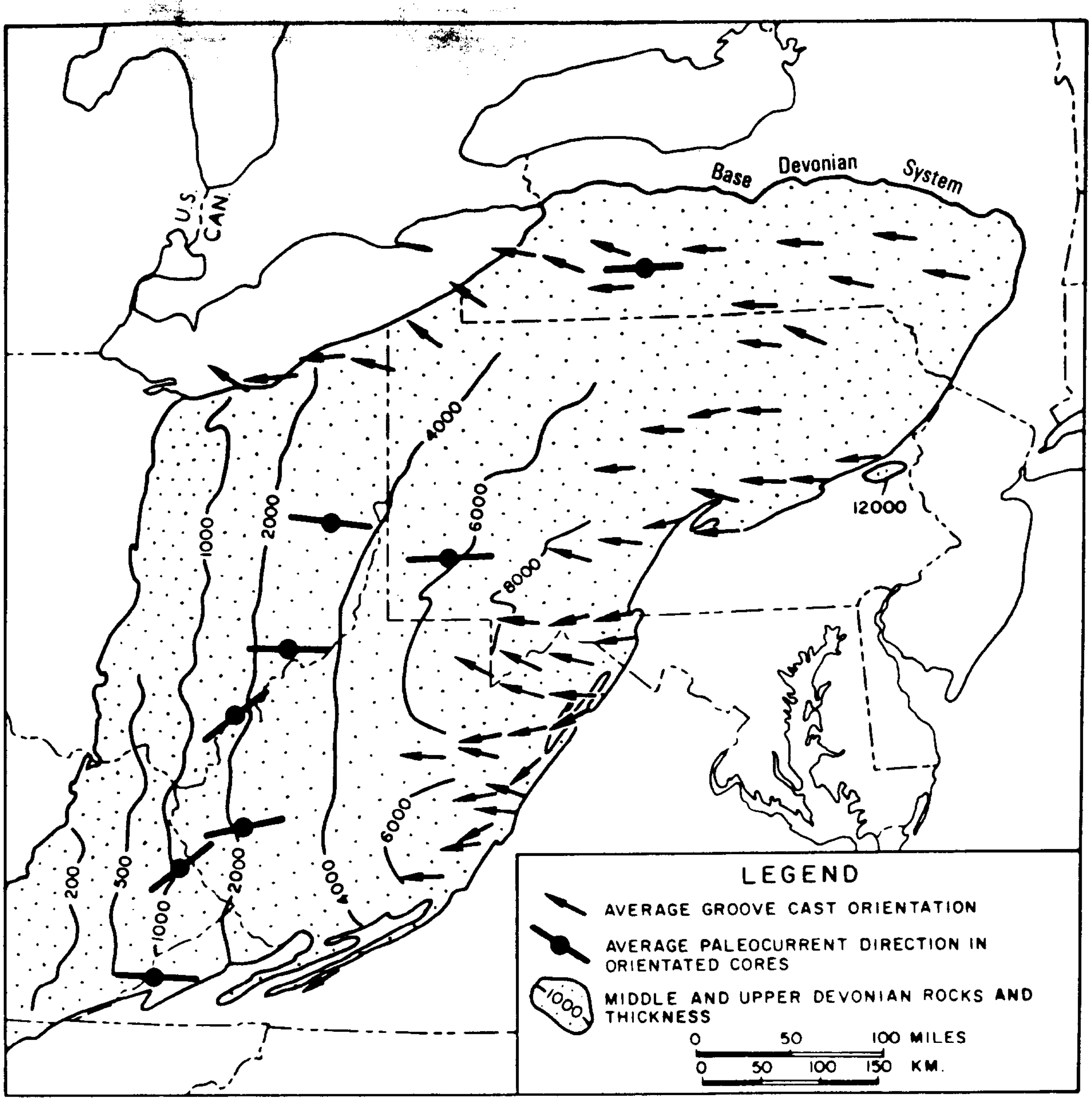


FIGURE 3: GENERALIZED PALEOCURRENT MAP OF DEVONIAN SEDIMENTS AND THICKNESS OF UPPER DEVONIAN IN APPALICHIAN BASIN. NOTE WESTWARD UNIFORMITY OF FLOW (POTTER et al., 1980, FIG. 1).

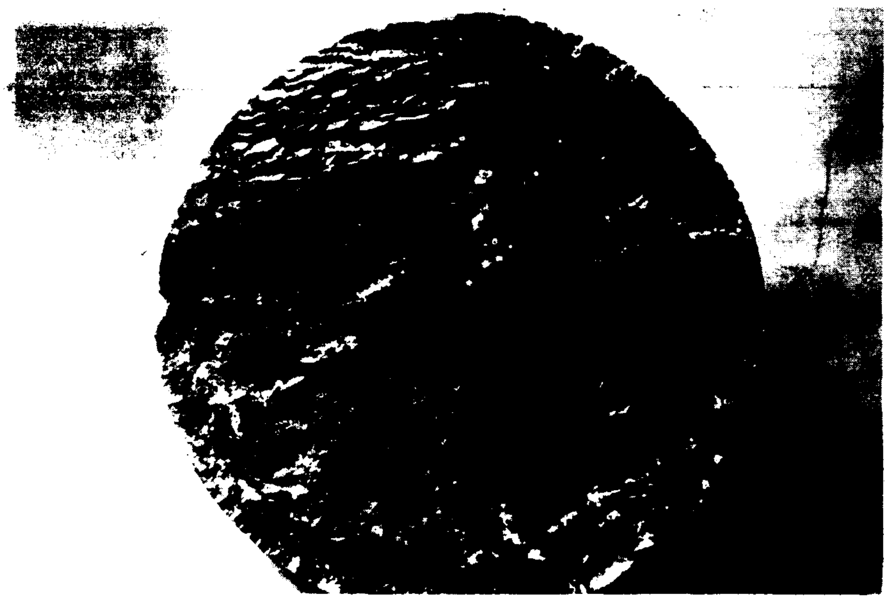


FIGURE 4: ORIENTATED WOOD FRAGMENTS (TOP) AND SMALL SCALE SOLE MARKS (BOTTOM) IN DEVONIAN SHALES ARE READILY OBSERVED IN CORES FROM MOST PARTS OF THE APPALACHIAN BASIN AND EASY TO MEASURE. NOTE UNIFORM ORIENTATION OF VERY SMALL SCALE SOLE MARKS AND EARLY SILT-FILLED FRACTURE AT RIGHT ANGLES.

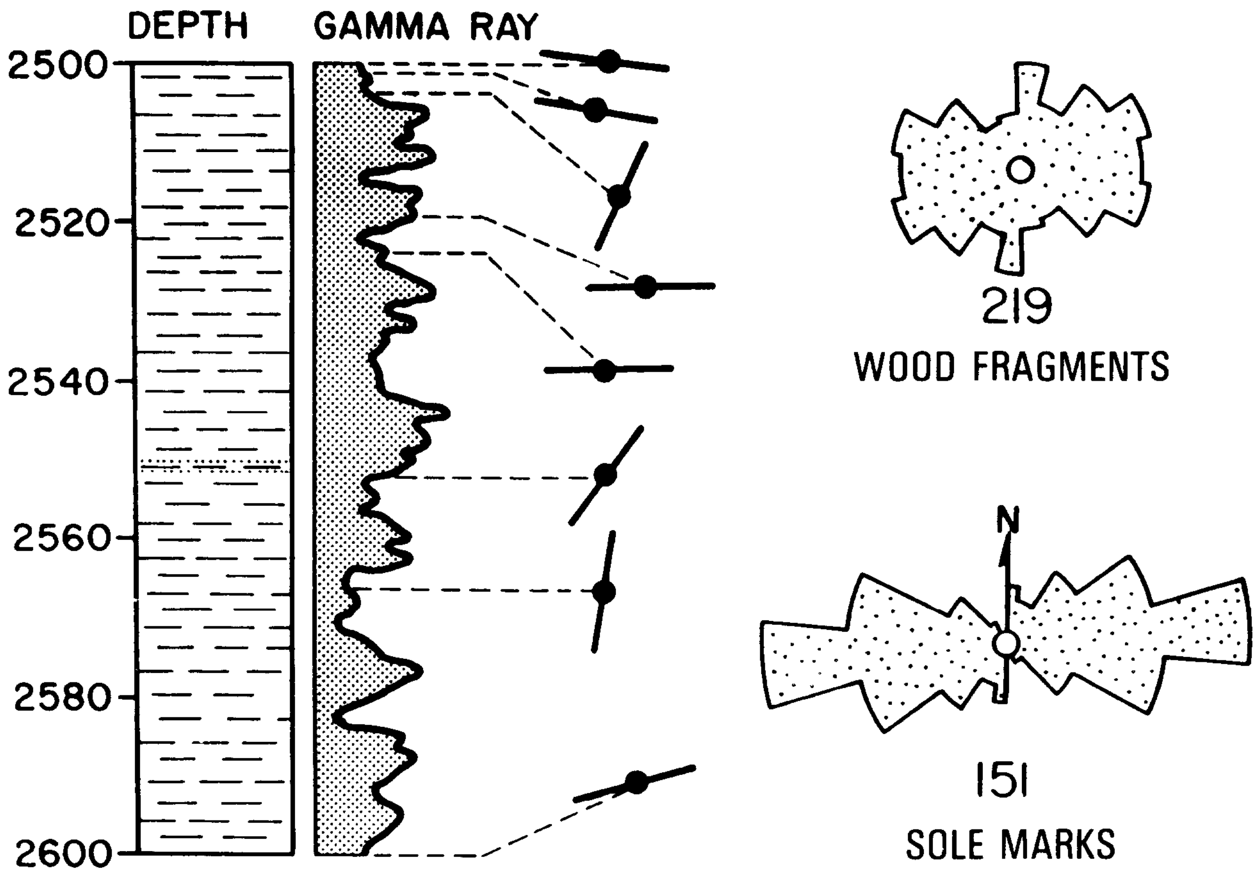
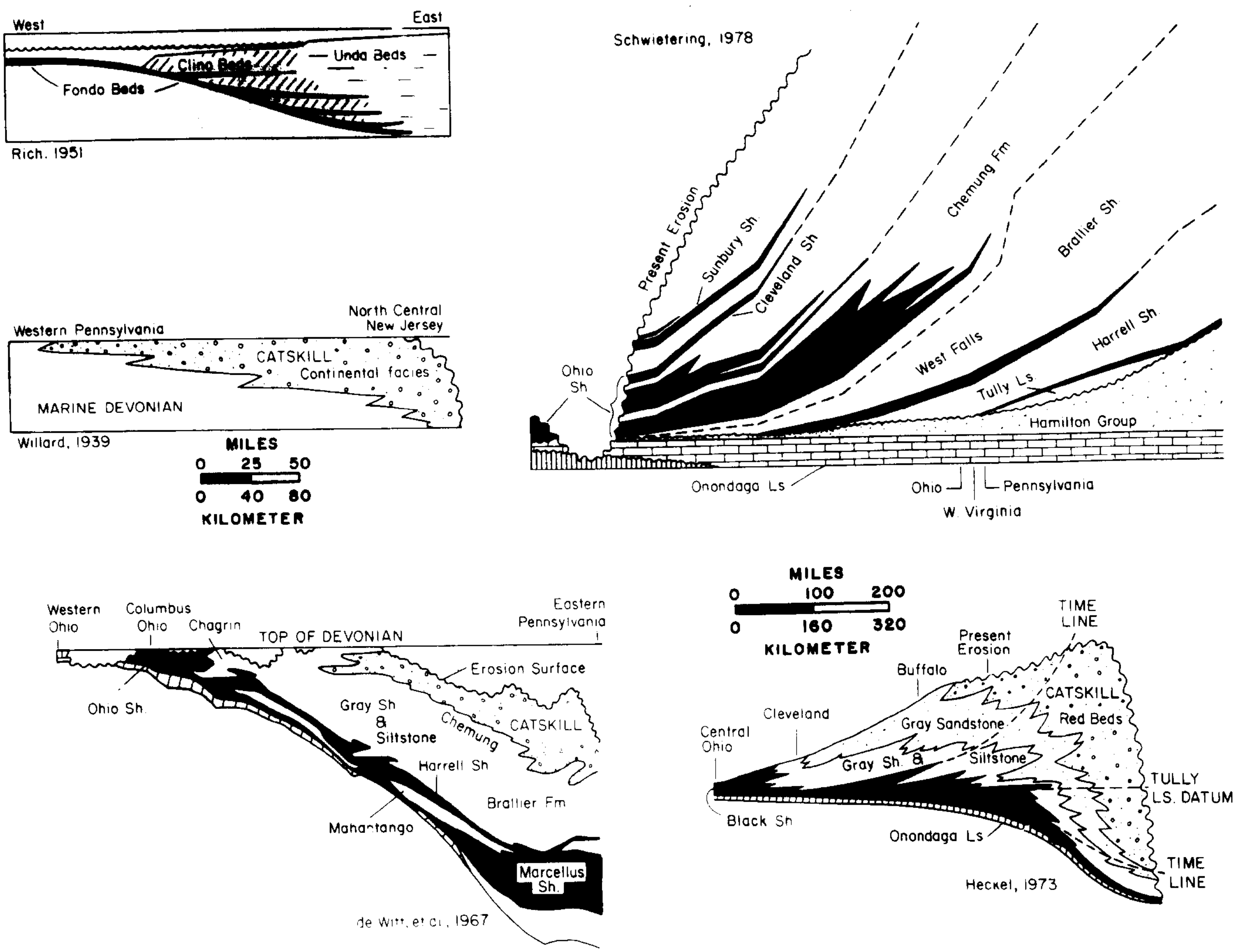


FIGURE 5: ORIENTATION OF WOOD FRAGMENTS AND SOLE MARKS IN ORIENTED CORE OF DEVONIAN SHALE (NATIONAL FUEL GAS SUPPLY CORP. NO. 6213, EASTERN GAS SHALES PROJECT, NEW YORK NO. 1 CORE, ALMOND TWP., ALLEGHENY CO., NEW YORK). CURRENT ROSES AT RIGHT SHOW DISTRIBUTION OF ALL OBSERVATIONS IN CORE.

EAST-WEST BASINWIDE SECTIONS



NORTHEAST - SOUTHWEST BASINWIDE SECTION

OBLIQUE TO DEPOSITIONAL STRIKE

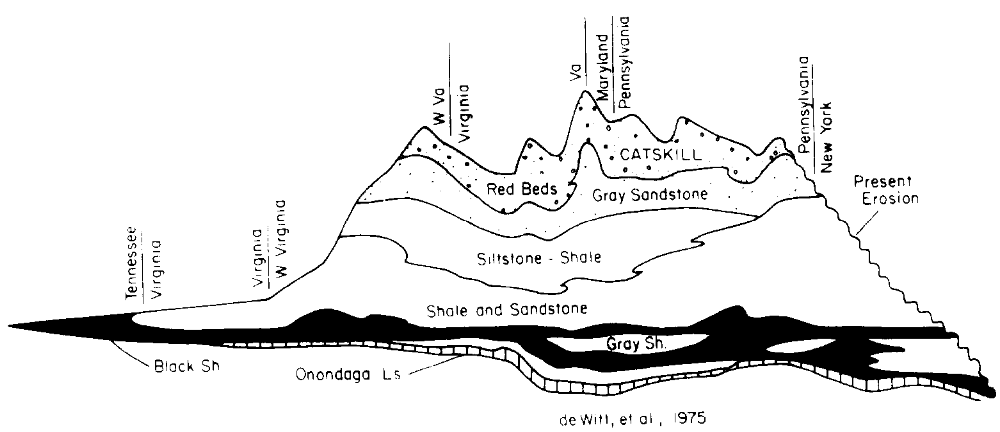


FIGURE 6: CHANGING PERCEPTIONS OF DEVONIAN STRATIGRAPHY OF THE APPALACHIAN BASIN.

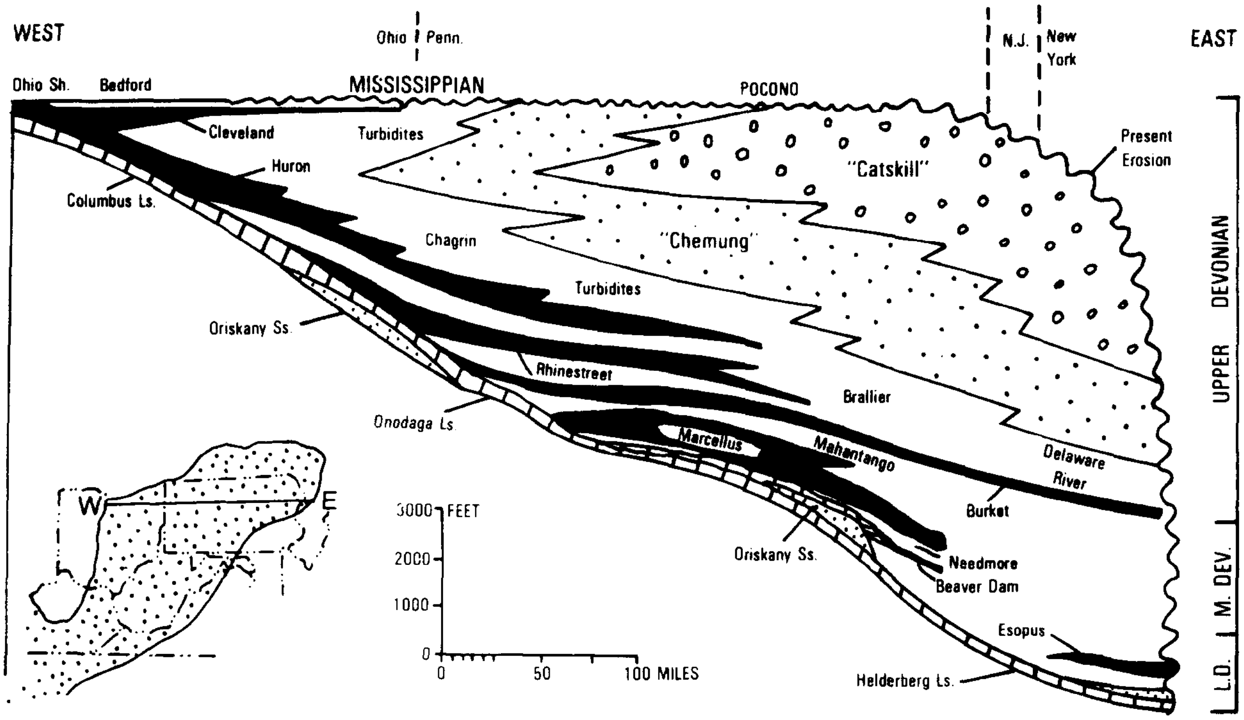


FIGURE 7: GENERALIZED EAST-WEST CROSS SECTION FROM NORTH-CENTRAL OHIO TO EASTERN PENNSYLVANIA (POTTER et al., 1980, Pl. 1).

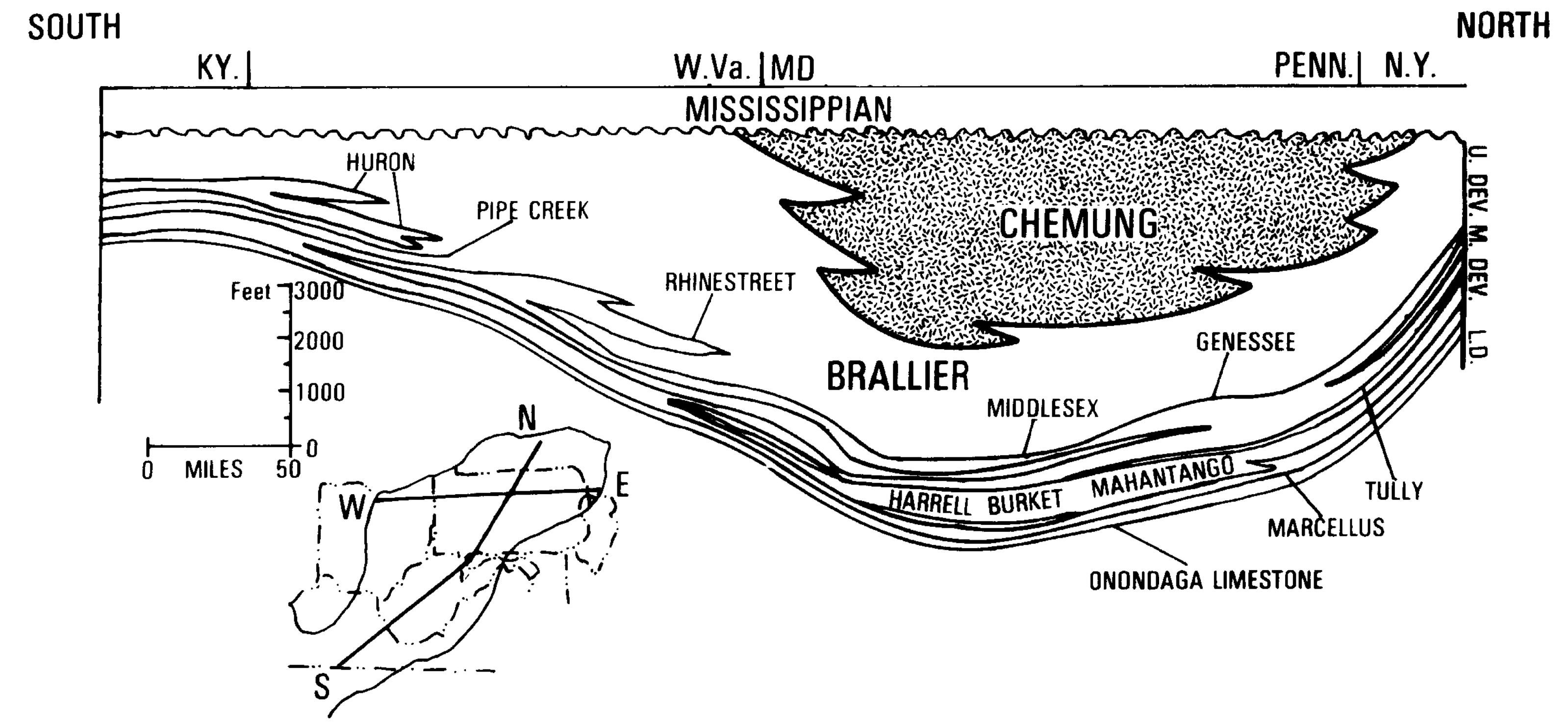


FIGURE 8: TRANSVERSE SECTION FROM TENNESSEE INTO WESTERN NEW YORK

DEVONIAN-MISISSIPPIAN BASIN MODEL

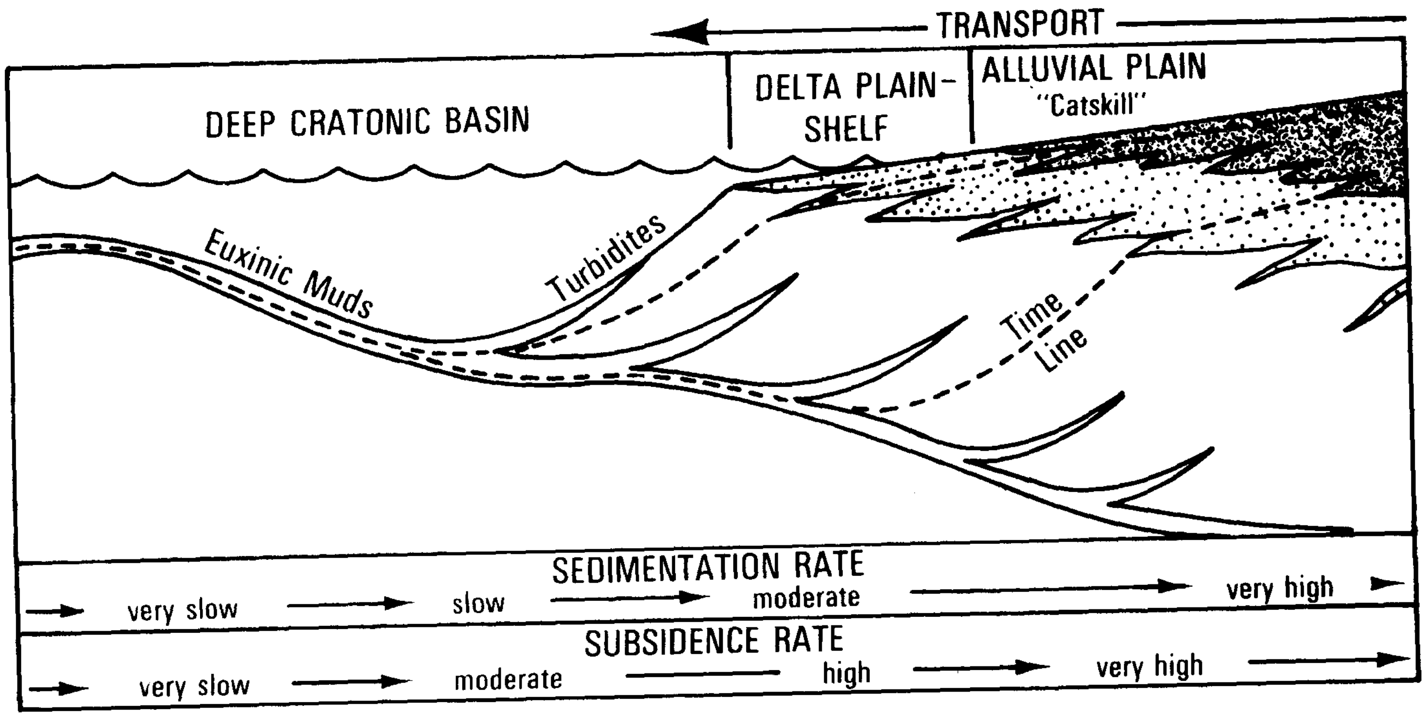


FIGURE 9: IDEALIZED DOWN DIP, LONGITUDINAL SECTION OF APPALACHIAN BASIN (POTTER et al, 1980, FIG. 7)

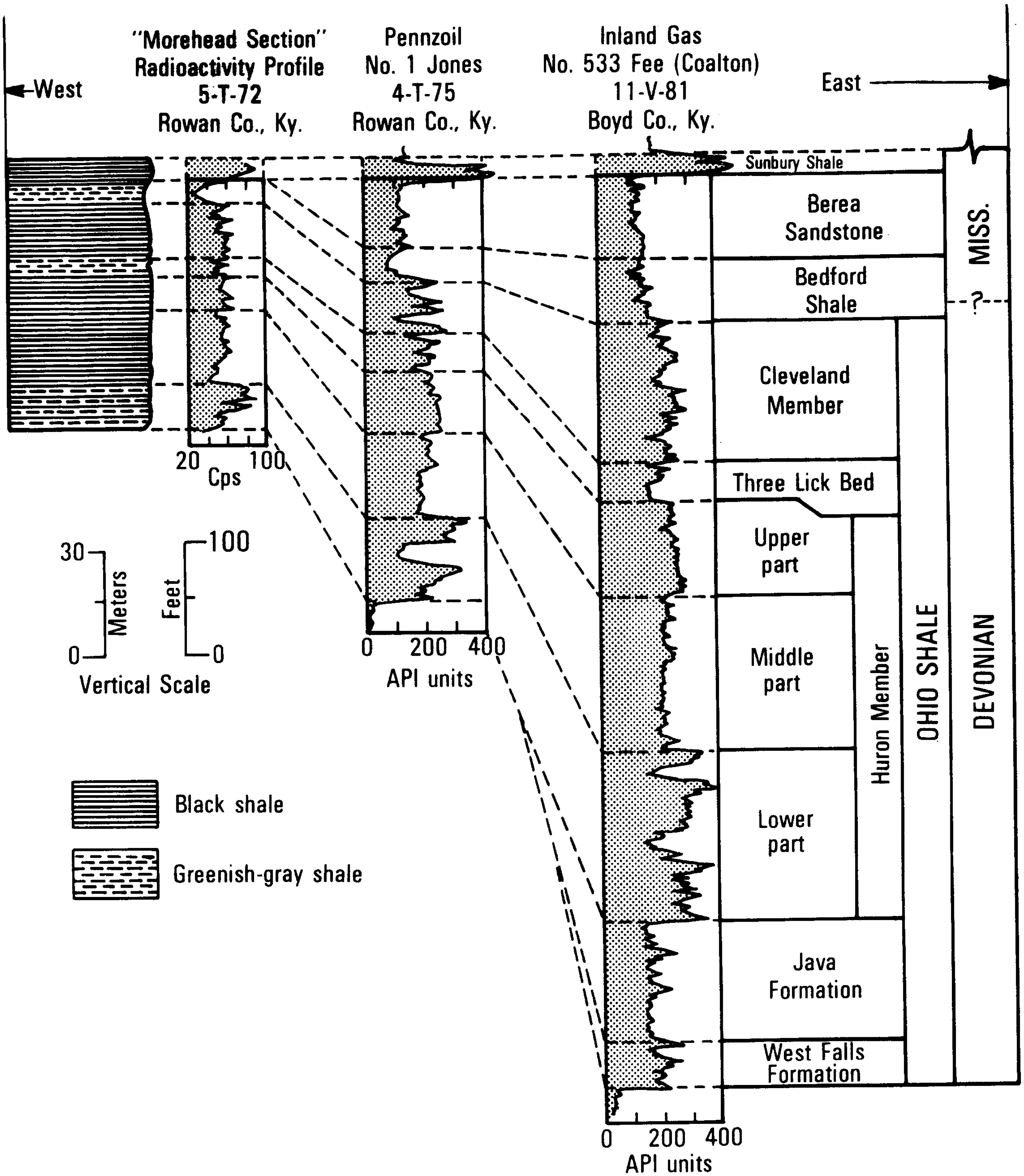


FIGURE 10: OUTCROPS CAN BE READILY CORRELATED TO THE SUBSURFACE BY COMPARING SCINTILLOMETER SURVEYS TO THE STANDARD GAMMA RAY LOGS OF THE SUBSURFACE (MODIFIED FROM ETTENSOHN et al., 1979, FIG. 3). SECTION EXTENDS EAST-WEST DOWN STRUCTURAL DIP ABOUT 40 MILES IN EASTERN KENTUCKY.

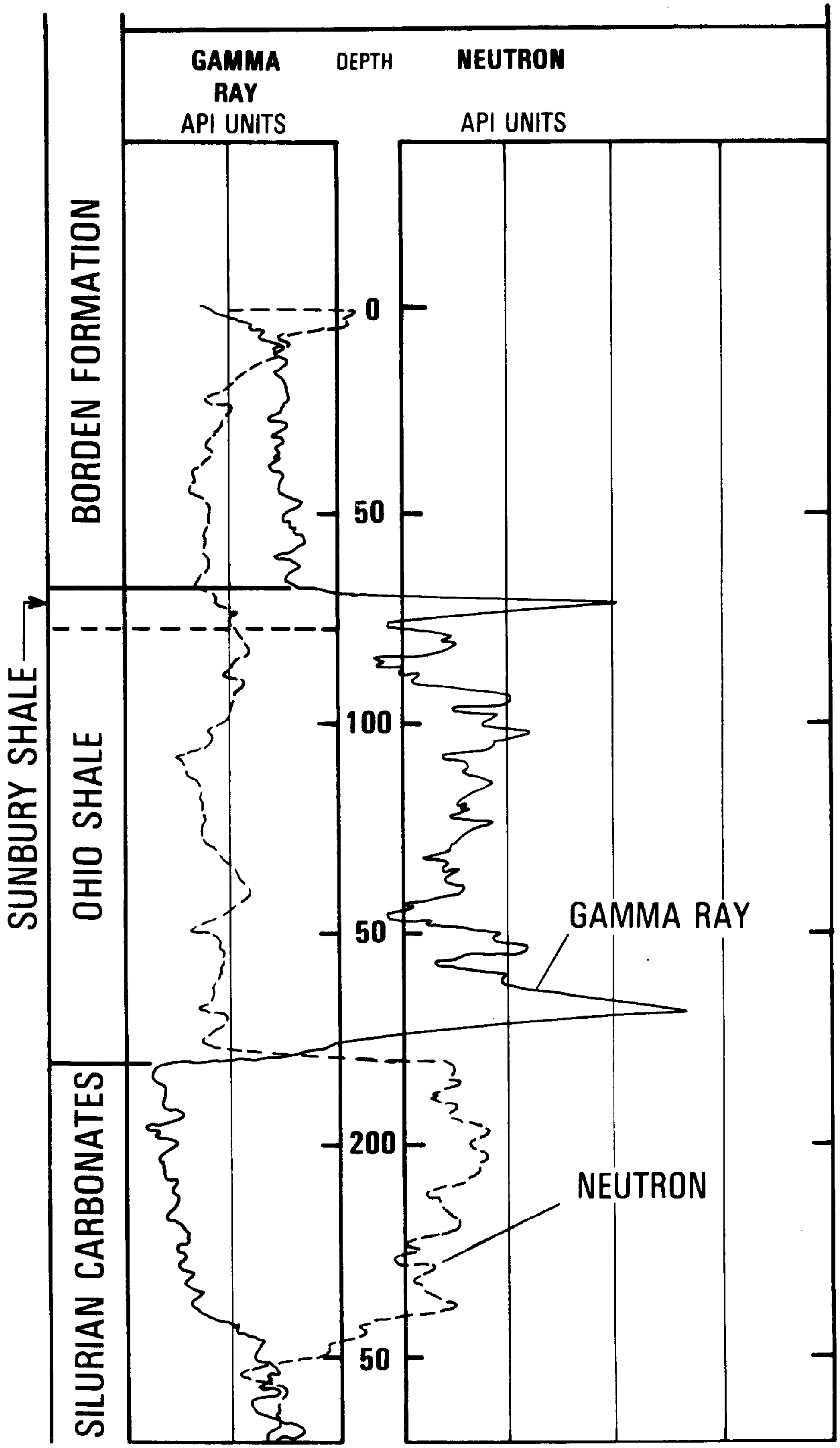


FIGURE 11: WIRE LINE LOG SHOWS SHARP BASE OF BLACK SHALE WHICH GRADES UPWARD INTO GRAY SHALE. RO-CO CORP., NO 4(0) WALLACE HEIRS, 13-0-67, ESTILL CO., KY. A SIMILAR GRADATION CAN BE SEEN ON A MUCH SMALLER SCALE, WHERE BLACK SHALES ARE INTERBEDED WITH GREENISH-GRAY SHALES (FIG. 14).

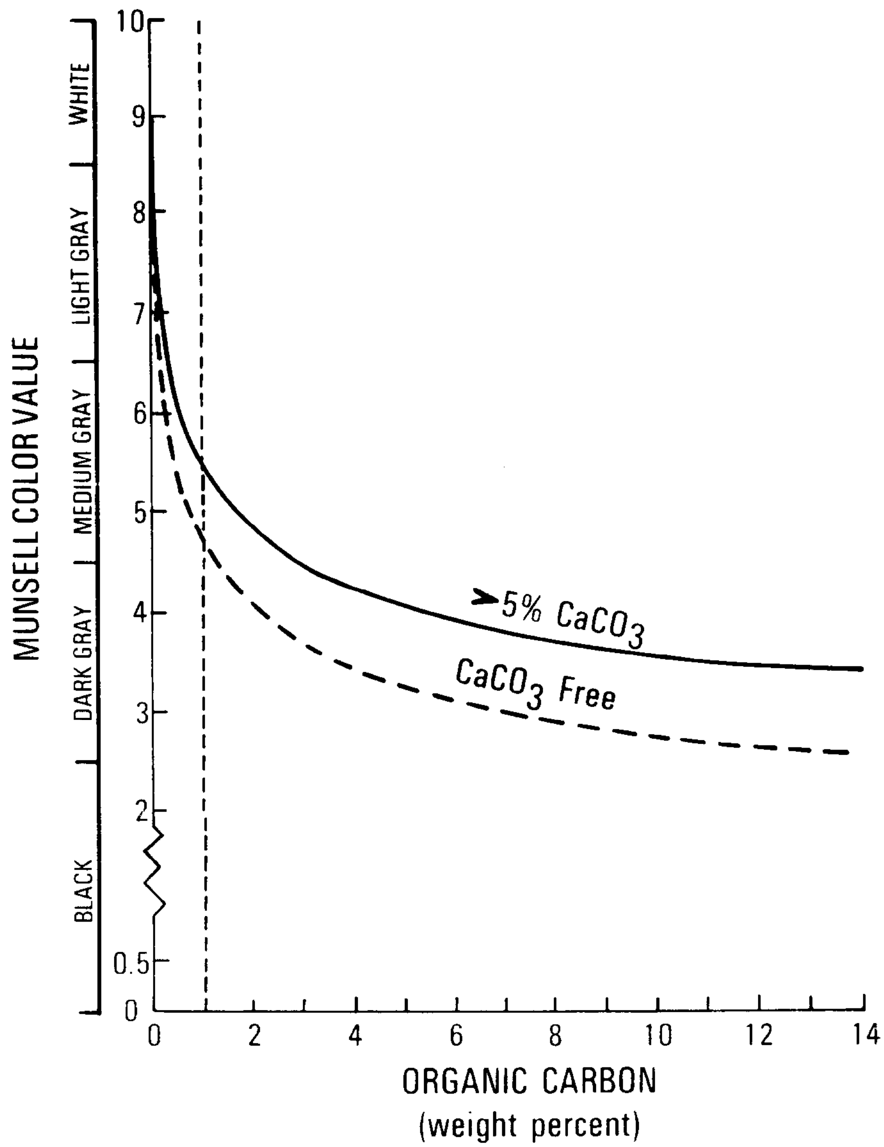


FIGURE 12: INCREASE IN ORGANIC CARBON PRODUCES DARKER COLORS (HOSTERMAN AND WHITLOW, 1980, FIG. 1). COLORS WERE DETERMINED ON PRESSED PELLETS OF GROUND SHALE; WHEN WHOLE SHALES ARE USED, SUCH CURVES WILL BE SHIFTED DOWNWARD TOWARD DARKER COLORS.

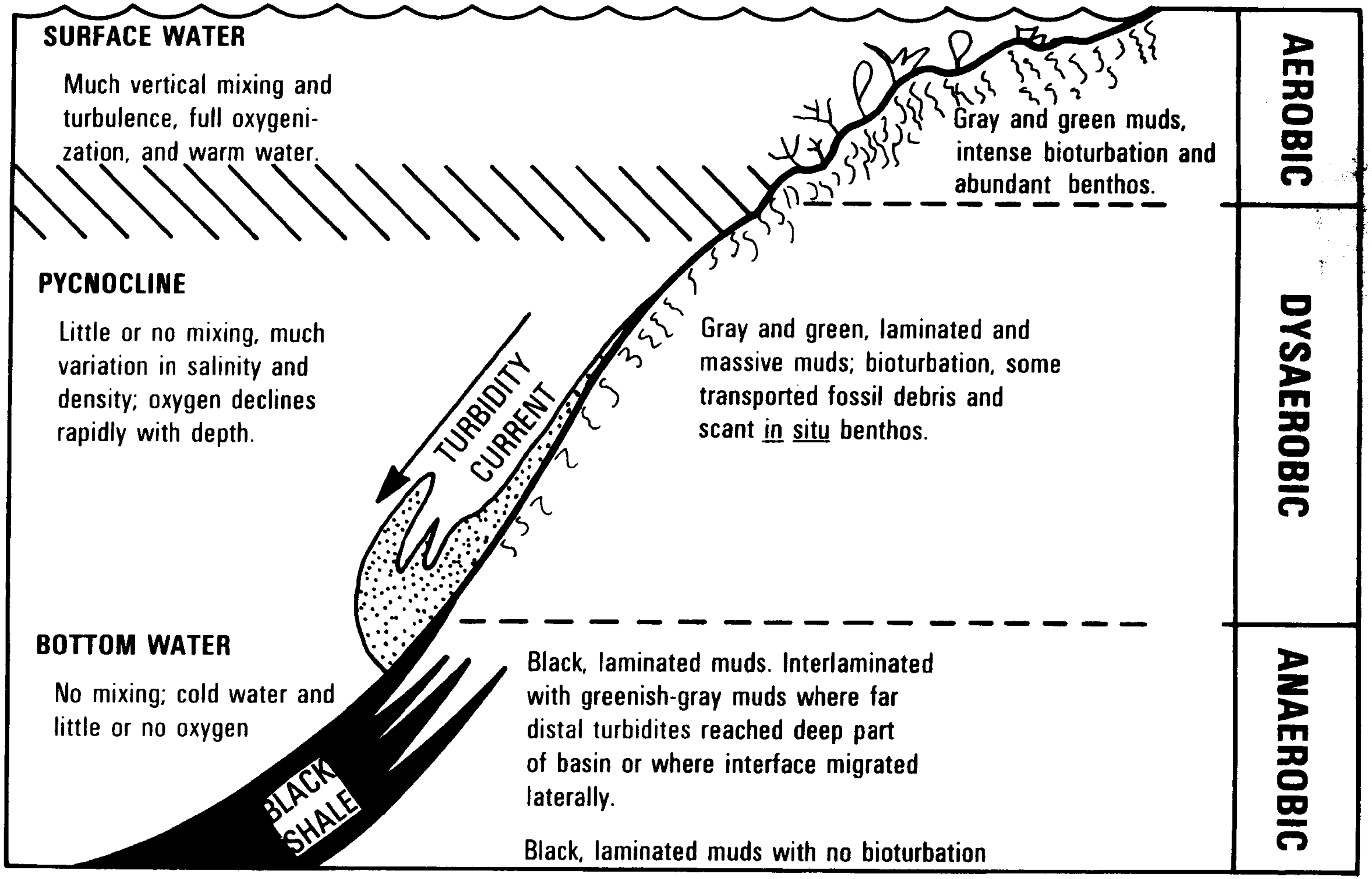


FIGURE 13: SHALE COLOR, LAMINATION AND BIOTA ARE SYSTEMATICALLY RELATED TO THE OVERLYING WATER MASSES IN MOST SHALY BASINS AND NOTICEABLY SO IN THE DEVONIAN SHALES OF THE APPALACHIAN BASIN. MODIFIED FROM DIVERSE SOURCES.

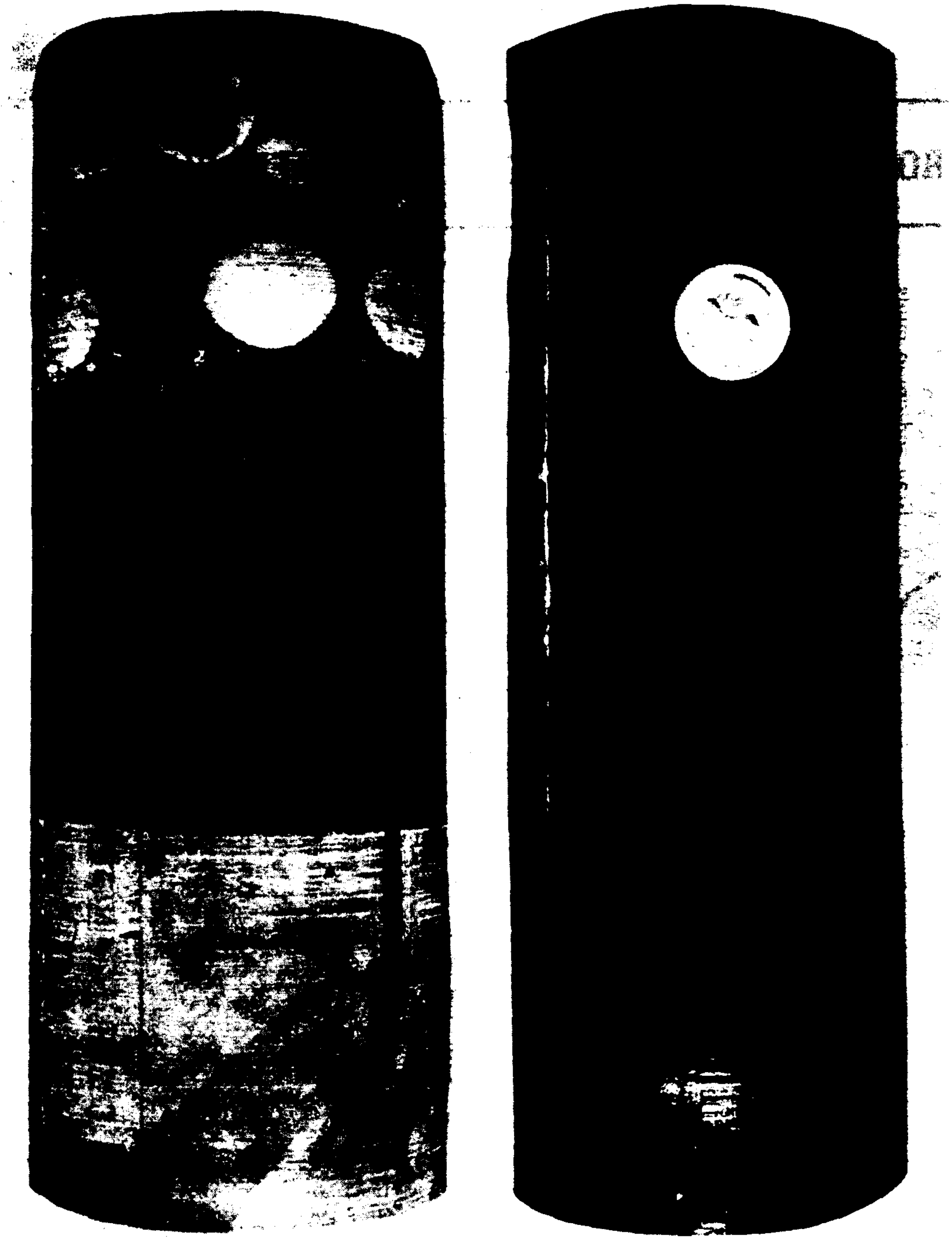


FIGURE 14: BURROWING IN THE DEVONIAN SHALE IS LARGELY CONFINED TO THE GREENISH-GRAY SHALE BUT SOME BURROWS EXTEND DOWNWARD INTO NUTRIENT-RICH BLACK SHALE, WHERE BOTTOM FEEDERS BURROWED INTO BLACK MUDS FOR NUTRIENTS. COMPARE WITH FIGURE 13. NOTE SHARP BASE AND GRADATIONAL TOP OF BOTH BLACK SHALES PLUS CARBONATE CONCRETIONS (WHITE) IN GREENISH-GRAY SHALE. ARROW POINTS DOWN HOLE.

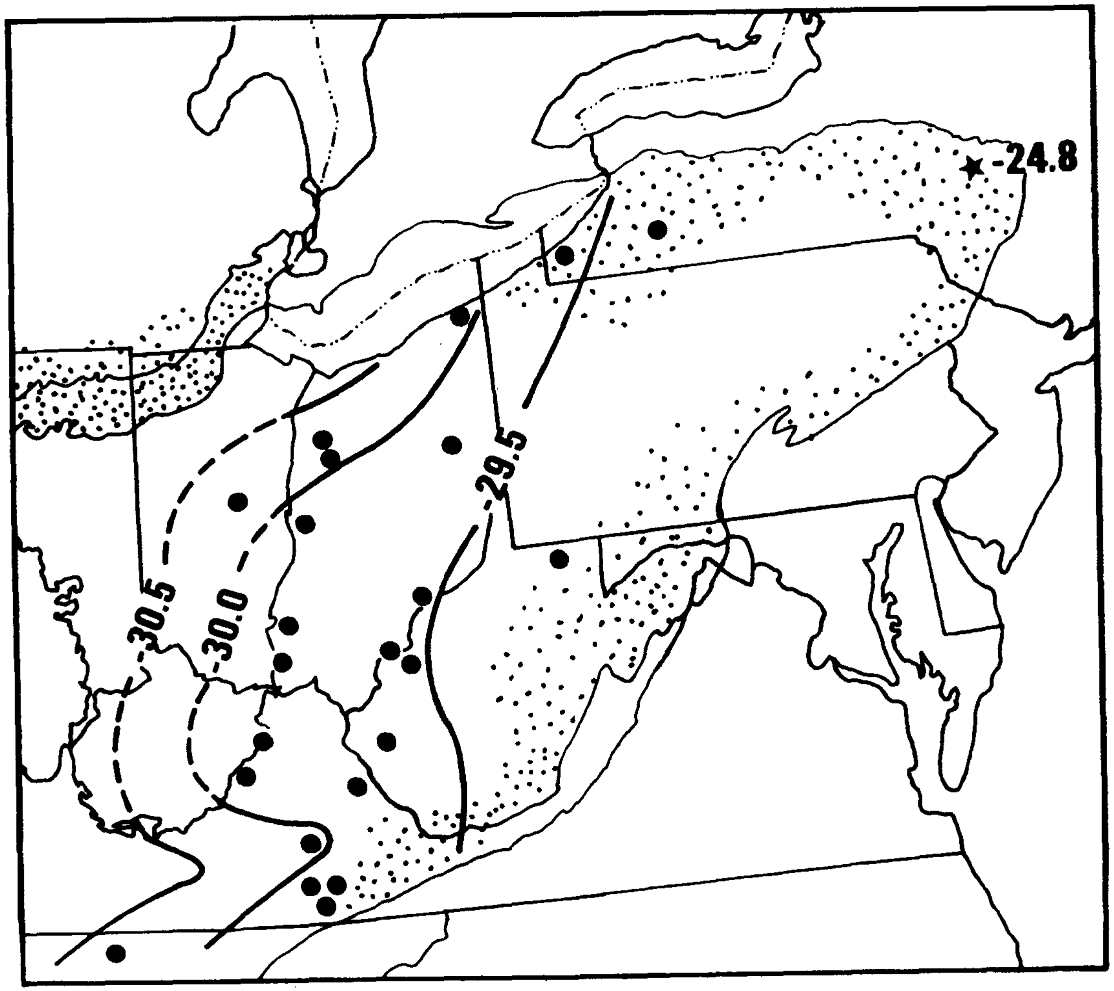


FIGURE 15: CARBON ISOTOPES IN THE LOWER HURON MEMBER OF THE OHIO SHALE BECOME LIGHTER WESTWARD; SOLID CIRCLES ARE CONTROL POINTS IN MARINE SEQUENCE AND STAR IS LOCATION OF A NON-MARINE EQUIVALENT.

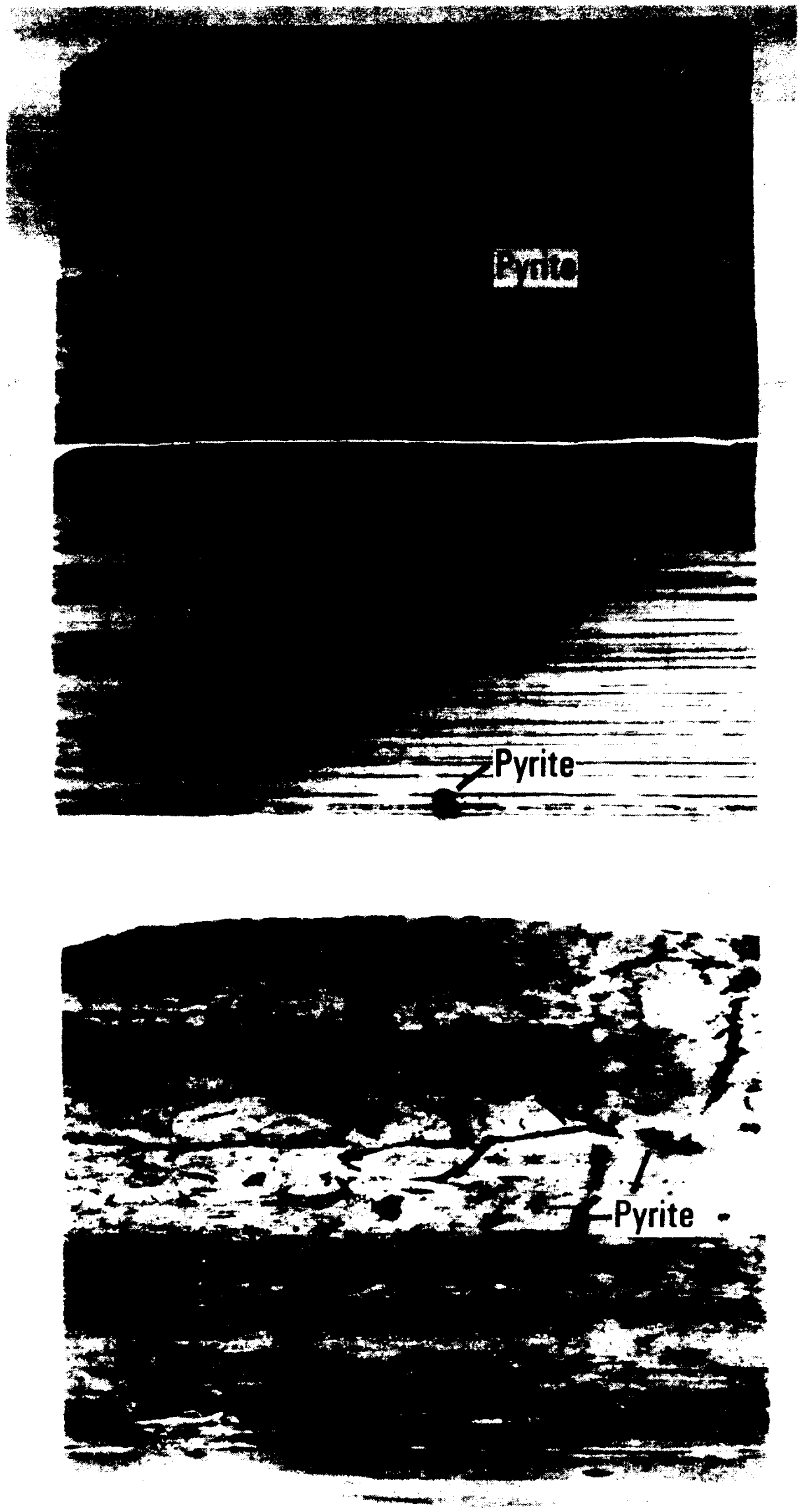


FIGURE 16: RADIOGRAPHS OF SHALE SHOW FINE DETAILS OF LAMINATION PLUS MINOR PYRITE NODULES (ABOVE) AS WELL AS BIOTURBATION AND PYRITE FILLED SYNERESIS FRACTURES (BELOW). EXAMPLES ARE ALL FROM DEVONIAN BLACK SHALE (NUHFER et al., 1979, FIGs. 8B AND 10D). CLUFF (1980) HAS COMPARABLE EXAMPLES FROM THE NEW ALBANY SHALE OF THE ILLINOIS BASIN.

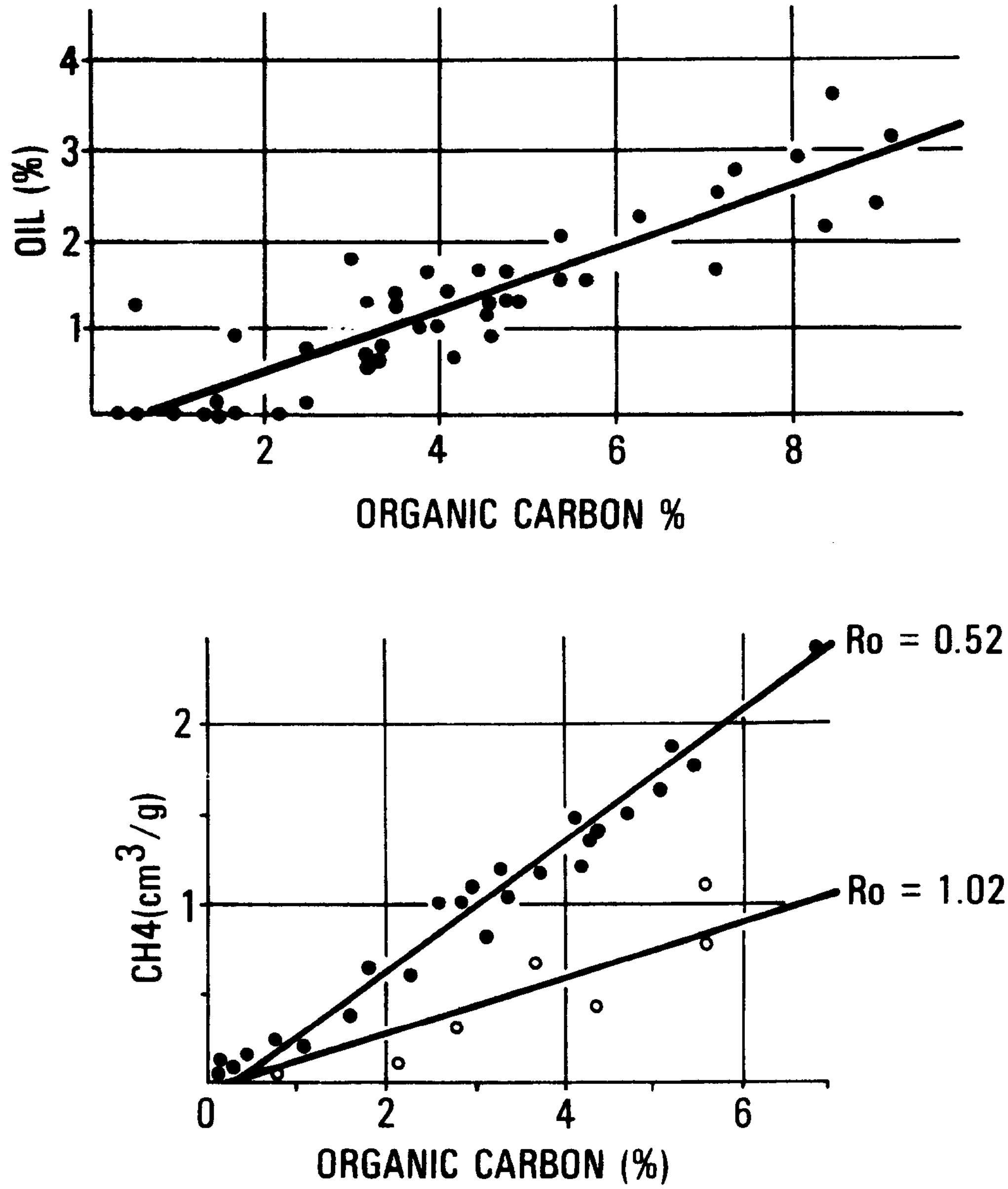


FIGURE 17: ORGANIC CARBON CONTROLS OIL RECOVERY AND GAS CONTENT IN THE DEVONIAN SHALES OF THE APPALACHIAN BASIN: (TOP) FISCHER ASSAY RESULTS FROM THE CORE OF OHIO SHALE IN PERRY COUNTY, KY. (LAMEY AND CHILDERS, 1977) AND (BOTTOM) GAS CONTENT VARIES WITH LEVEL OF THERMAL MATURITY AS INDICATED BY VITRINITE REFELCTANCE, Ro, IN CORES OF OHIO SHALE FROM MARTIN CO., KY. (SOLID CIRCLES) AND WISE CO., VIRGINIA (OPEN CIRCLES). DATA FOR BOTTOM FIGURE FROM VARIOUS QUARTERLY REPORTS OF THE MOUND LABORATORY (SEE FOR EXAMPLE, ZIELINSKI, 1980, TABLE 5B.

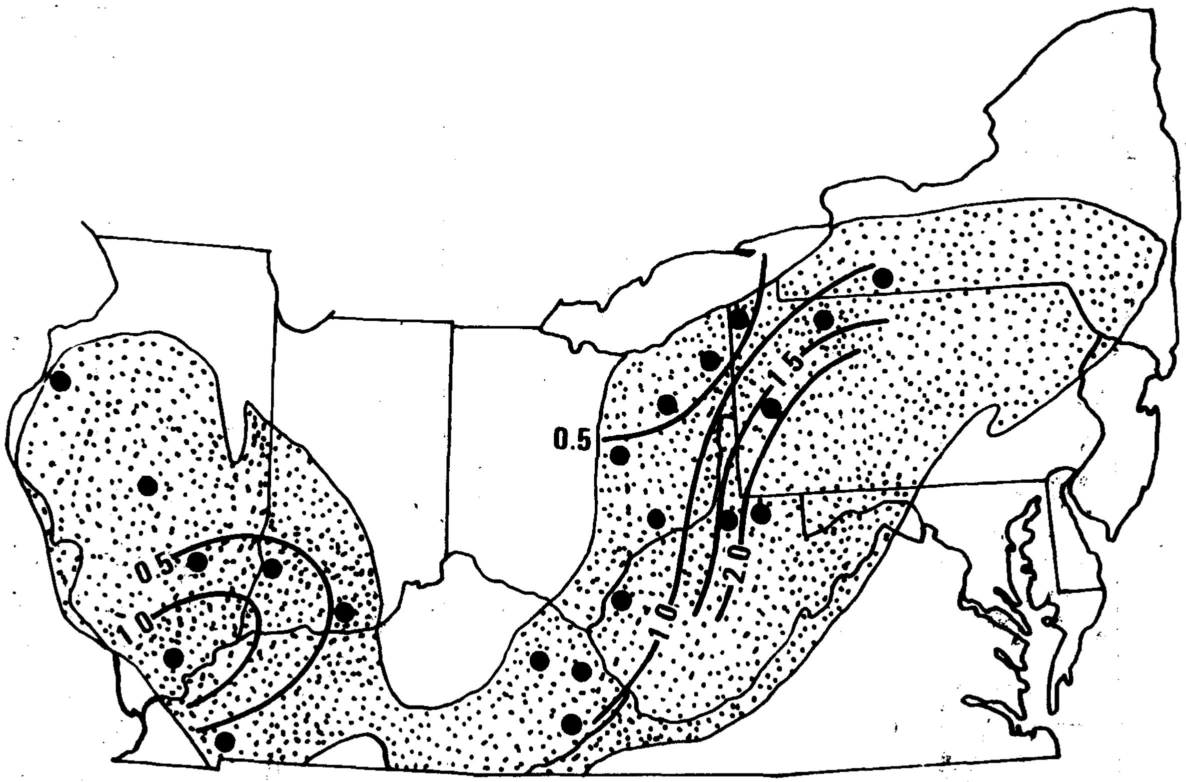


FIGURE 18: VITRINITE REFLECTANCE IN THE APPALACHIAN AND ILLINOIS BASINS INCREASES WITH THE DEPTH OF BURIAL

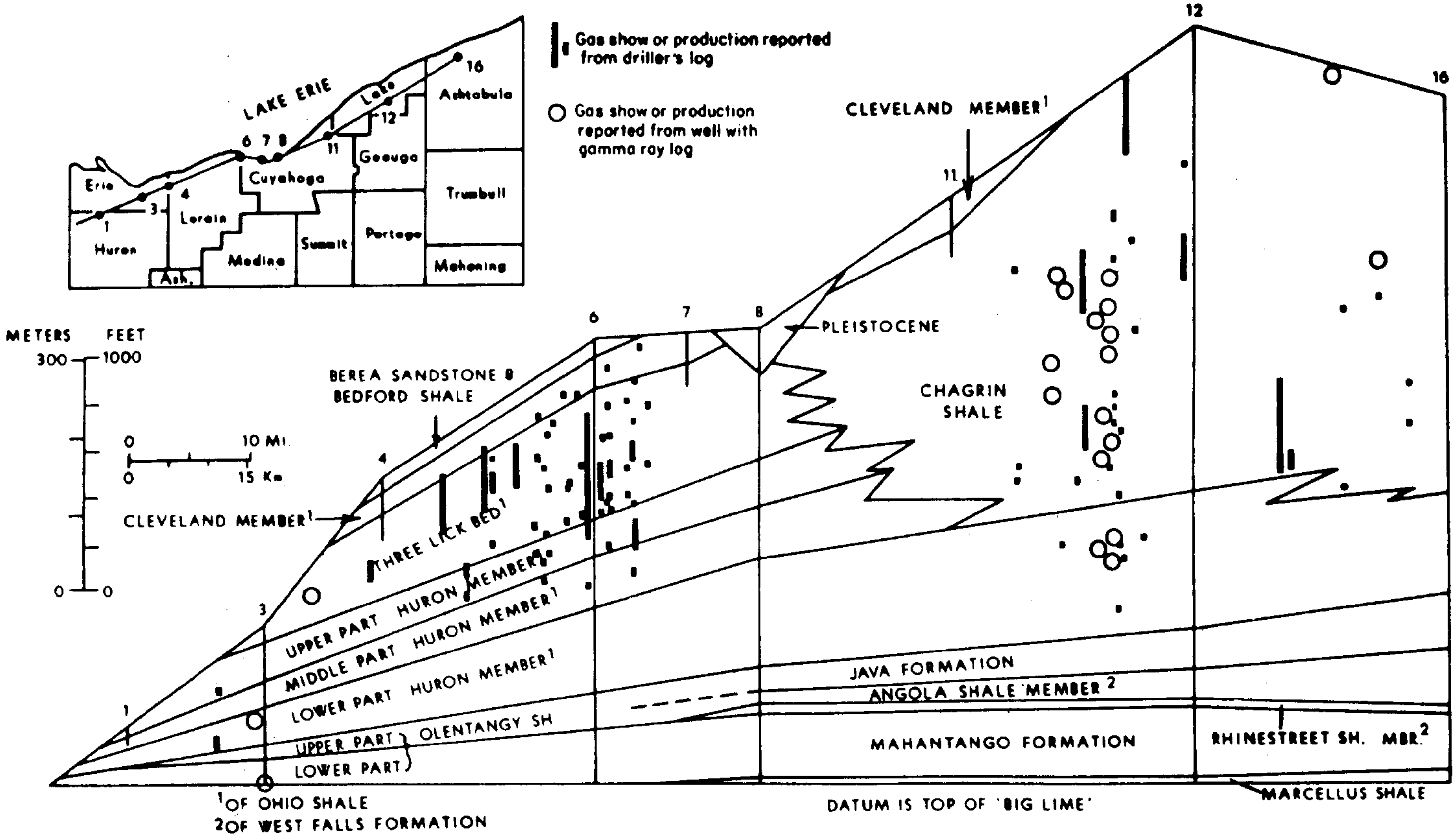


FIGURE 19: GAS SHOWS ALONG LAKE ERIE ARE MOST ABUNDANT IN THE CHAGRIN SHALE AND THE THREE LICK BED (BROADHEAD AND POTTER, 1980, FIG. 3).

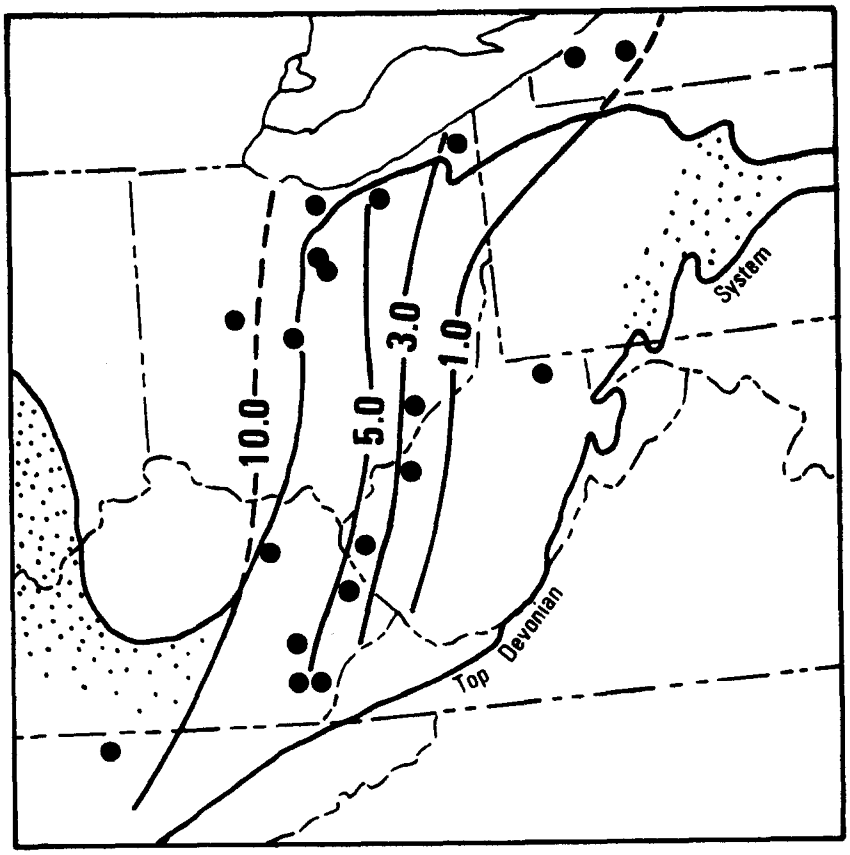
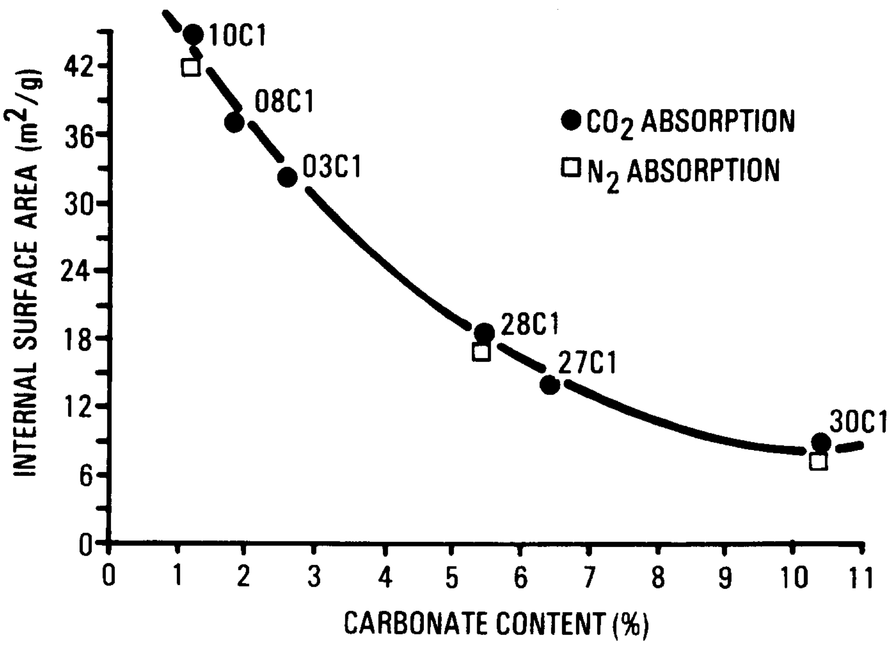


FIGURE 20: INDIVIDUAL BLACK SHALE UNITS SUCH AS THIS ONE, THE LOWER HURON MEMBER OF THE OHIO SHALE AND THE DUNKIRK SHALE OF NEW YORK, HAVE LOWER ORGANIC CARBON CONTENT TO THE EAST. THIS TREND IS PERPENDICULAR TO PALEOCURRENTS (FIG. 3), BUT DIVERGES SOMEWHAT FROM THERMAL MATURITY TREND (FIG. 18).



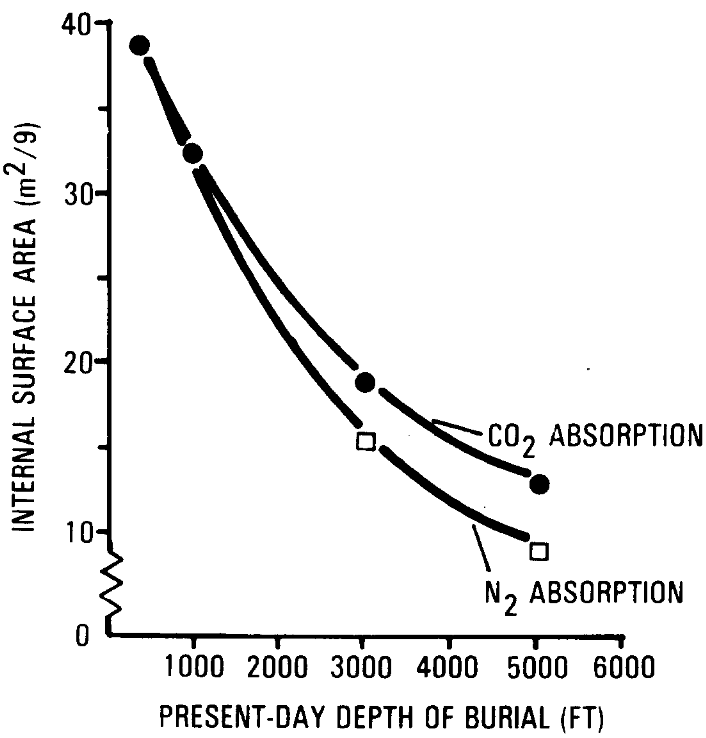


FIGURE 21: INTERNAL SURFACE AREA DECREASES WITH DEPTH OF BURIAL (BOTTOM) AND WITH INCREASING CARBON CONTENT (TOP) IN THE NEW ALBANY SHALE OF THE ILLINOIS BASIN (THOMAS AND FROST, 1980, FIGS. XIV-1 AND XIV-2). DECREASE OF SURFACE AREA WITH INCREASING DEPTH IMPLIES REDUCED MATRIX POROSITY. ADSORPTION OF CO_2 IS PROPORTIONAL TO TOTAL POROSITY, N_2 RESPONDS ONLY TO PORES LARGER THAN 5Å. THUS PORE SIZE AS WELL AS TOTAL POROSITY DECREASES WITH DEPTH. DECREASE OF SURFACE AREA WITH CARBONATE CEMENT SUGGESTS THAT CARBONATE FORMS A PORE-FILLING CEMENT IN DEVONIAN SHALES. HOW COMMON ARE THESE RELATIONSHIPS IN OTHER SHALY BASINS?

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